

Results from T2K: Indication of Electron Neutrino Appearance in a Muon Neutrino Beam

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(University of Toronto, York University) on behalf of the T2K Collaboration



Fermilab Seminar, July 18, 2011

Outline



- Review of neutrino oscillations
- Overview of the T2K experiment
- Data collected by T2K
- Analysis chain
 - Flux prediction
 - Near detector measurement
 - Far detector selection
 - Systematic uncertainties
- Far detector data and interpretation
- Acknowledgements & Conclusions

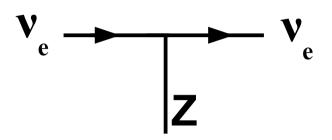
Reminder About Neutrinos



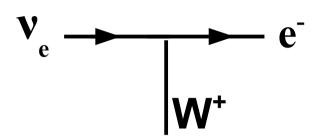
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Weakly interacting isospin partners of charged leptons:

Neutral current



Charged current



Neutrinos have mass:

Mass eigenstates: v_1, v_2, v_3 Flavor eigenstates: v_e, v_μ, v_τ

$$|v_l\rangle = \sum_{i=1}^3 U_{li}|v_i\rangle$$

 Produced and interact as flavor eigenstates, but propagate as mass eigenstates:

$$|\nu_l(L)\rangle = \sum_{i=1}^{3} U_{li} e^{-i m_i^2 L/2E} |\nu_i(0)\rangle$$

Neutrino Oscillations



• Parameterization of the PMNS mixing matrix U_{i} :

$$\begin{pmatrix} v_{e} \\ v_{\mu} \\ v_{\tau} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} v_{1} \\ v_{2} \\ v_{3} \end{pmatrix}$$

- δ is CP violating phase
- Probability to oscillate depends on energy (E), distance traveled (L), the mixing matrix U and the differences in the squared neutrino masses :

$$\begin{pmatrix}
P_{\alpha \to \beta} = \delta_{\alpha \beta} - 4 \sum_{i>j} \Re (U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2(\frac{\Delta m_{ij}^2 L}{4 E}) \\
+ 2 \sum_{i>j} \Im (U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin(\frac{\Delta m_{ij}^2 L}{2 E})
\end{pmatrix}$$

Knowledge of Oscillation Parameters



Three mixing angles, two mass squared differences, CP phase

$$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$$

$$\Delta m_{12}^2 = 7.59 \pm 0.20 \times 10^{-5} \ eV^2$$

SNO, KAMLAND, SK

$$\sin^2(2\theta_{23}) > 0.92 \quad (90\% \quad C.L.) \qquad \Delta m_{23}^2 = 2.43 \pm 0.13 \times 10^{-3} \ eV^2$$

$$\Delta m_{23}^2 = 2.43 \pm 0.13 \times 10^{-3} \ eV^2$$

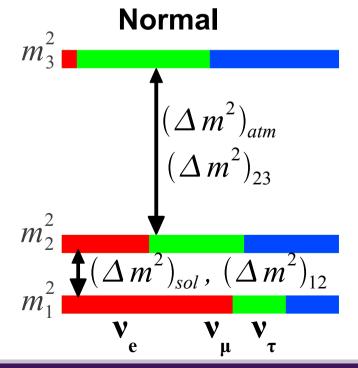
SK, K2K, MINOS

$$\sin^2(2\theta_{13}) < 0.12 \quad (90\% \quad C.L.)$$
 MINOS(2010), CHOOZ $\delta = ?$

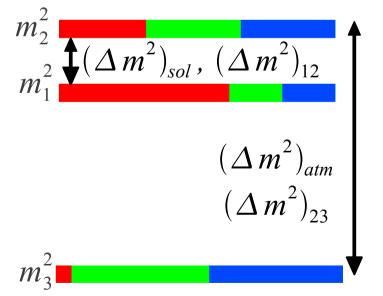
Ambiguity in sign of

$$m_3^2 - m_2^2$$

Two possible mass hierarchies



Inverted



Measuring θ_{13}



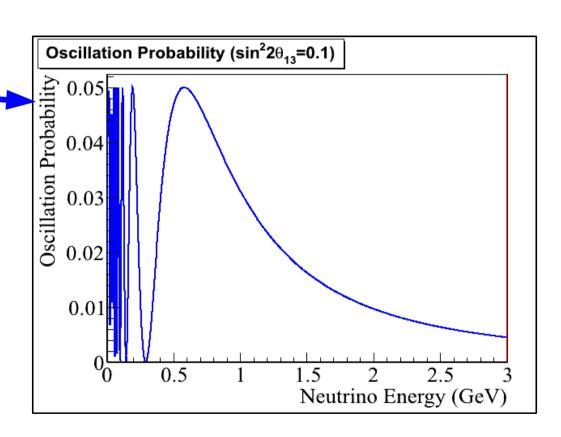
Accelerator based experiments - access to θ_{13} through oscillations of muon neutrinos to electron neutrinos:

$$P(\nu_{\mu} \rightarrow \nu_{e}) = \sin^{2}\theta_{23}\sin^{2}2\theta_{13}\sin^{2}\frac{\Delta m_{23}^{2}L}{4E_{\nu}} + \text{subleading terms}$$

 v_e appearance probability for L=295 km and $sin^2(2\theta_{13})$ =0.1 (ignoring subleading terms)

Design experiment with v_{μ} beam peaked at first oscillation maximum

Search for v_e appearance



Measuring $\boldsymbol{\theta}_{_{13}}$ is an important first step to searching for CP violation in $\boldsymbol{v}_{_{\boldsymbol{e}}}$ appearance

Outline



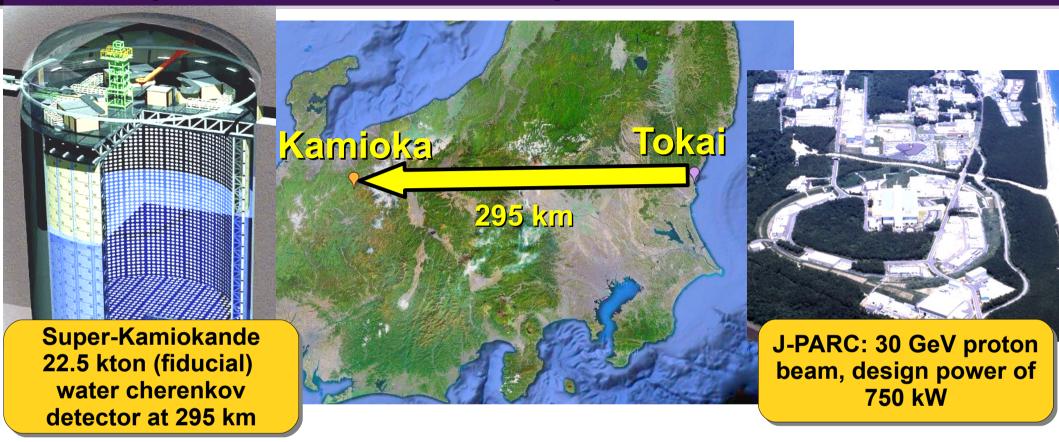




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T2K (Tokai to Kamioka) Experiment





Experiment's immediate goals:

Focus of this talk

• Search for v_e appearance:

$$P(\nu_{\mu} \rightarrow \nu_{e}) \approx \sin^{2}\theta_{23} \sin^{2}2\theta_{13} \sin^{2}\frac{\Delta m_{32}^{2} L}{4 E_{\nu}}$$

• Precision $\nu_{_{\mu}}$ disappearance

The T2K Collaboration















~500 collaborators, 59 institutes, 12 countries

Canada

TRIUMF
U. Alberta

U.B. Columbia

U. Regina

U. Toronto

U. Victorial York. U.

France

CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany

U. Aachen

Italy

IPNF, U. Roma IPNF, U. Napoli IPNF, U. Padova IPNF, U. Bari

Japan

ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
U. Tokyo

Poland

A. Soltan, Warsaw H. Niewodnicsanki, Cracow

T.U. Warsaw

U. Silesia, Katowice

U. Warsaw

U. Wroklaw

Russia

INR

S. Korea

Chonnam N.U.

Dongshin U.

Seoul N.U

Spain

IFIC, Valencia
IFAE(Barcelona)

Switzerland

U. Bern
U. Geneva
ETH Zurich

United Kingdom

Imperial C. London Queen Mary U.L. Lancaster U. Liverpool U. Oxford U. Sheffield U. Warwick U. STFC/RAL STFC/Daresbury

USA

Boston U. B.N.L.

Colorado S. U.

Duke U.

Louisiana S. U.

Stony Brook U.

U. C. Irvine

U. Colorado

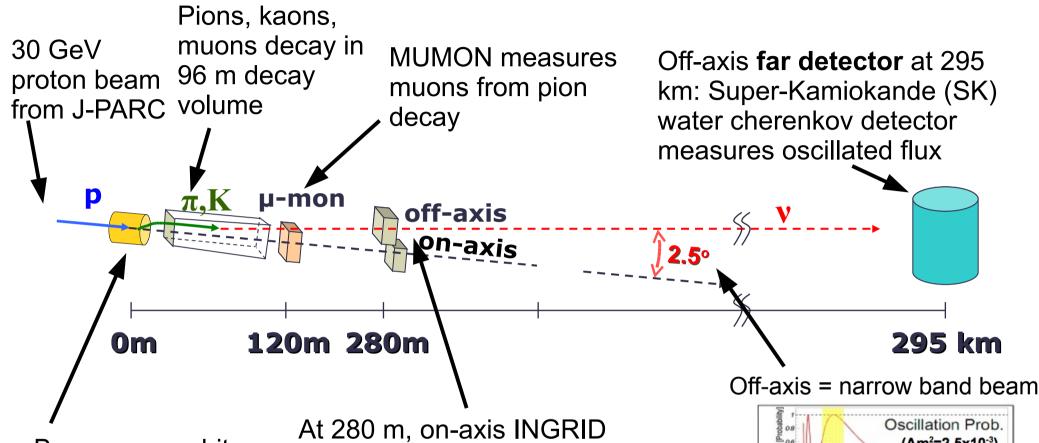
U. Pittsburgh

U. Rochester

U. Washington

T2K Overview



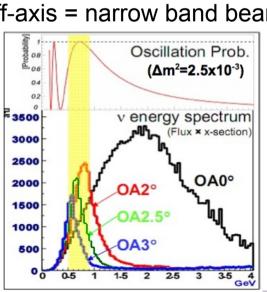


Beam on graphite target

3 magnetic horns focus positively charged hadrons

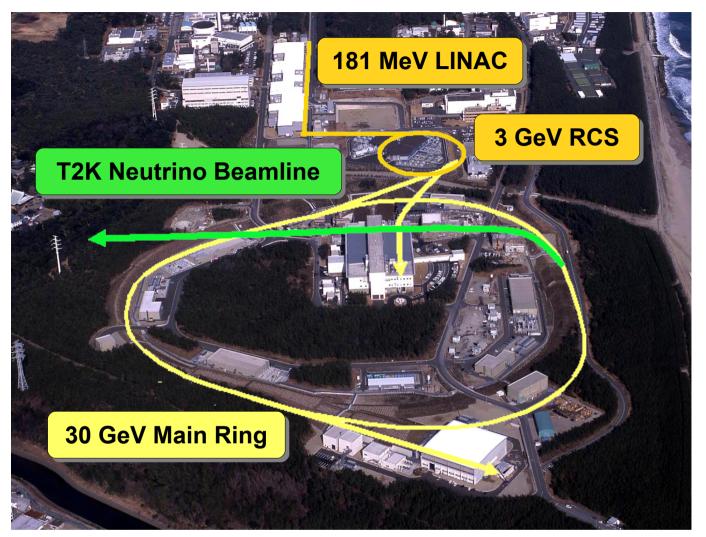
At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

Off-axis **near detector**: ND280 detector measures spectra for various neutrino interactions



J-PARC Accelerator

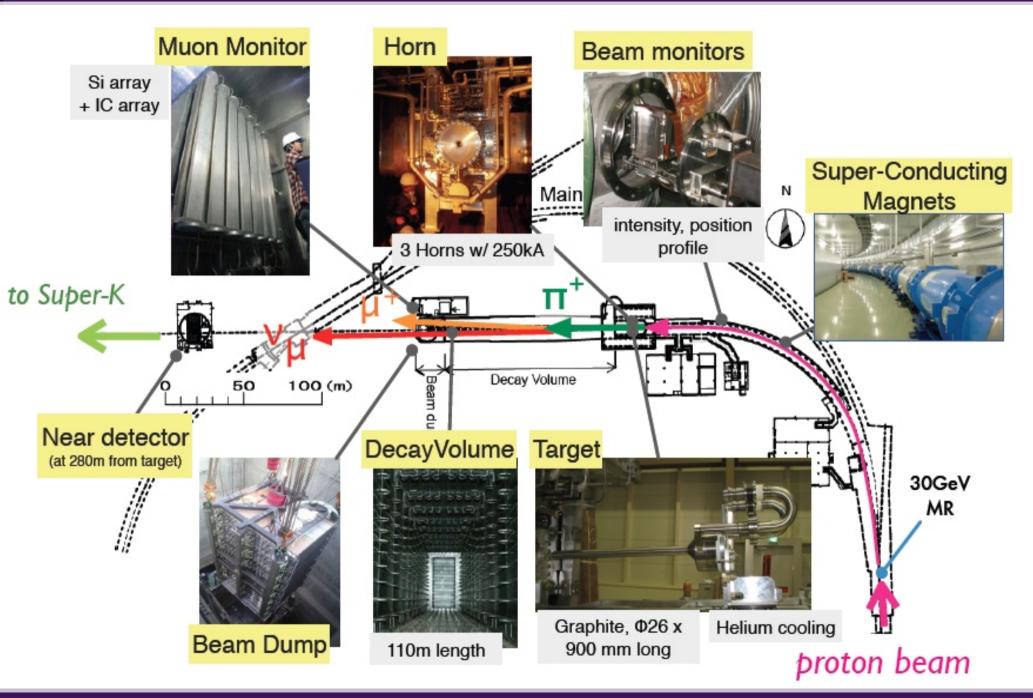




- Located in Tokai village
- Completed in 2009
- Accelerator
 Design/Performance
 - Design goal of 750 kW
 - 30 GeV protons to neutrino beamline
 - Reached 145 kW before earthquake

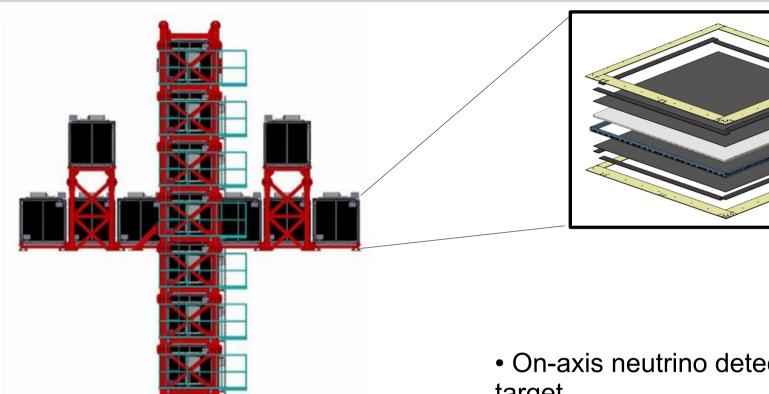
J-PARC Neutrino Beam Line

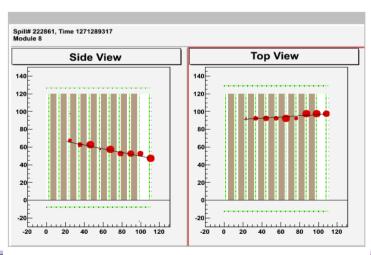




INGRID On-axis Detector







- On-axis neutrino detector at 280 m from target
- 16 modules (14 in cross configuration)
- Modules consist of iron and scintillator layers
- Measures neutrino beam profile and rate

ND280 (Near) Off-axis Detector



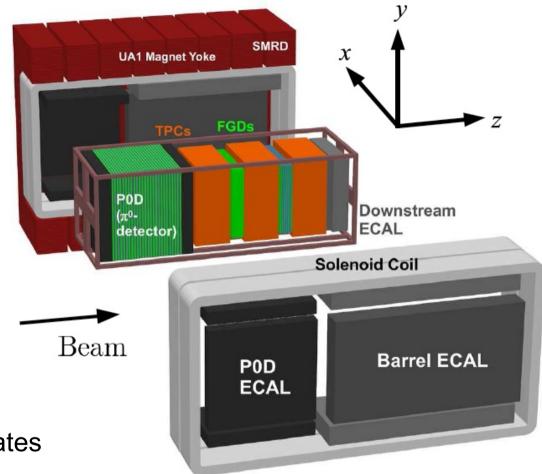
• 0.2 T UA1 magnet

Used in this analysis

- Fine Grained Detectors (FGD)
 - Scintillator bars and water targets (FGD2)
 - Interaction mass and tracking
- Time Projection Chambers (TPC) momentum and dE/dx measurements

Important for future analyses

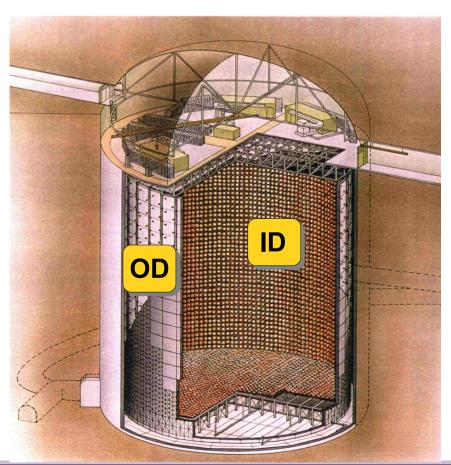
- POD π^0 detector measures NC π^0 rates
 - Scintillator planes interleaved with water and lead/brass layers
- Electromagnetic calorimeters measure EM showers from inner detectors
- SMRD muon detector installed in the magnet yoke detect muons, cosmics trigger, side muon veto



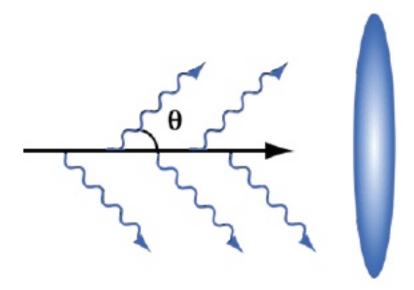
SK (Far) Detector



- 50 kton (22.5 kton fiducial volume) water cherenkov detector
- ~11,000 20" PMT for inner detector (ID) (40% photo coverage)
- ~2,000 outward facing 8" PMT for outer detector (OD): veto cosmics, radioactivity, exiting events
- Good reconstruction for T2K energy range



Cherenkov light produces a ring detected by the PMTs



Particle Identification at SK



Muons:

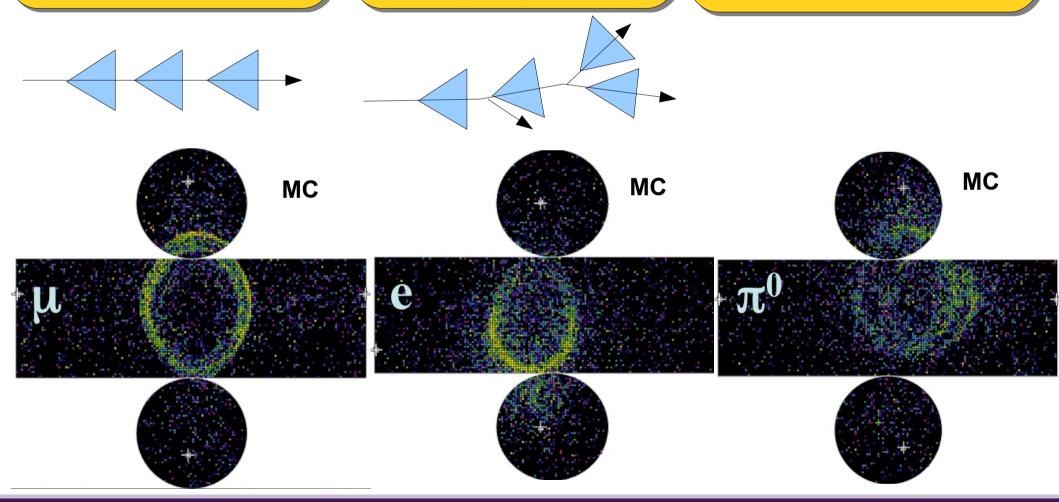
- Minimal scattering
- Ring has sharp edges

Electrons

- Electromagnetic shower
- EM scattering makes a "fuzzy" ring

Neutral Pions

• γ s from π^0 decays shower and look like electrons



Neutrino Interactions at T2K



Total (CC+NC)

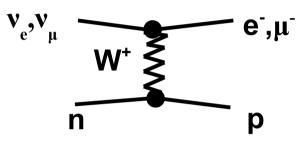
v Cross-sections

Total (CC)

CC Quasi-elastic

In region of interest for T2K:

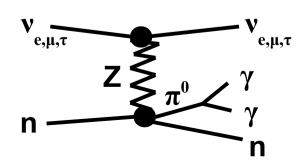
Large contribution from charge current quasi-elastic (CCQE)



T2K signal at SK

Significant $CC\pi$ component with additional pion in final state

 $NC\pi^0$ is significant background mode:



0.4 0.2 NC 1π⁰ 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 E_ν(GeV) T2K beam peak energy

Photons from π^0 can fake an electron

1.4

1.2

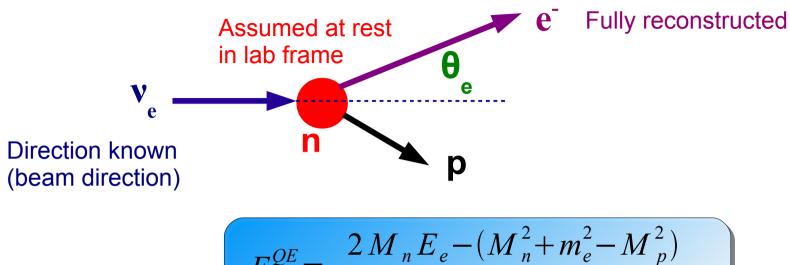
0.8

0.6

5/E (10⁻³⁸cm²/GeV)

Reconstructing the v Energy





$$E_{\nu}^{QE} = \frac{2M_{n}E_{e} - (M_{n}^{2} + m_{e}^{2} - M_{p}^{2})}{2[M_{n} - E_{e} + \sqrt{E_{e}^{2} - m_{e}^{2}\cos\theta_{e}}]}$$

- Only lepton in final state is reconstructed
- Can determine neutrino energy with assumptions:
 - Neutrino direction is known (beam direction)
 - Recoil nucleon mass is known
 - Target nucleon is at rest not exactly true, adds smearing to energy

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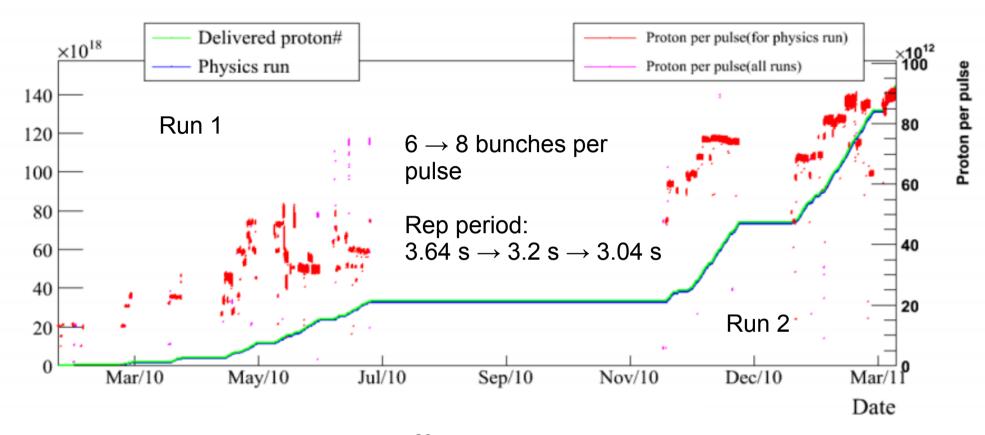


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Data Collected





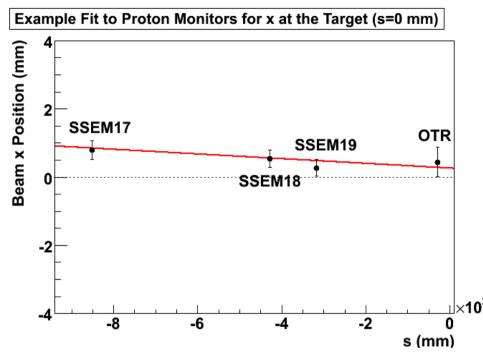


- Run 1+Run 2 data set = 1.43 x 10²⁰ POT for SK analysis
- Reached continuous running at 145 kW in Run 2 (50 kW in Run 1)
 - Increase bunches per pulse, increase protons per bunch, increase rep rate
- 2% of the design goal for T2K

Proton Beam Targeting



Proton beam orbit tuned with **SSEM**, **ESM**, **OTR** proton beam monitors and **MUMON**

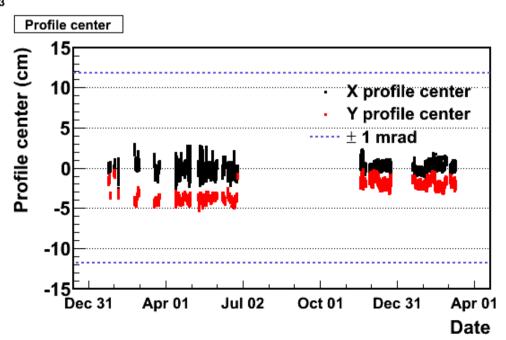


MUMON measured beam profile center stable within ±0.3 mrad

Fit to SSEM and OTR monitors gives position at target

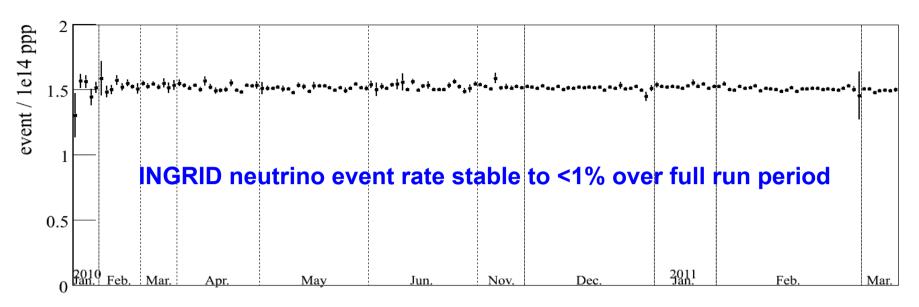
Uncertainty: 0.4 mm in x, 0.6 mm in y \rightarrow ~0.3 mrad uncertainty in v beam

1 mrad shift of neutrino beam = 2% shift in v peak energy



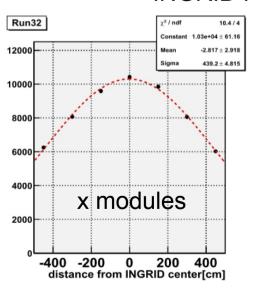
v Rate and Direction Stability

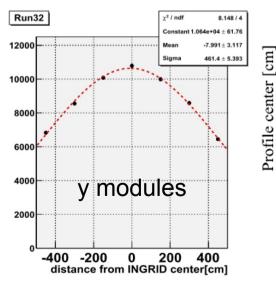




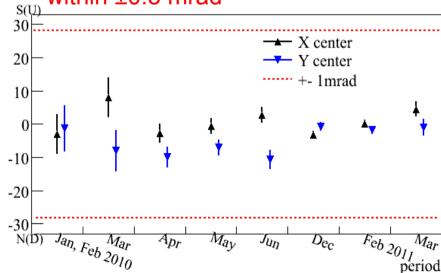
integrated day(1 data point / 1day)

INGRID Profiles





INGRID confirms beam direction within ±0.3 mrad



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Oscillation Analysis Flow



Flux Prediction

- Proton beam measurements
- Hadron production data

ND280 Measurement

- Inclusive v_µ CC measurement
- Output: $R_{ND}^{\mu,Data}/R_{ND}^{\mu,MC}$
- Measure v_e rate as cross-check

Neutrino Cross Sections

- Interaction models
- External cross section data

SK Measurement

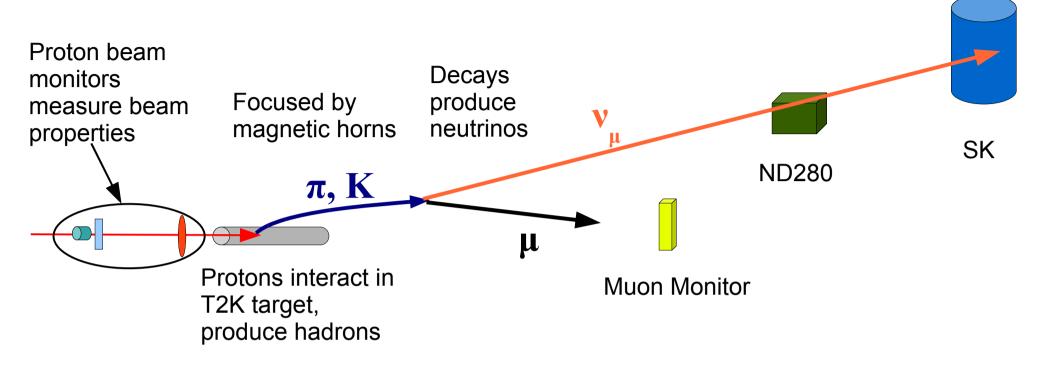
- Develop v_e CCQE candidate selection
- Simulate expectation: N_{SK}^{MC}
- Adjust normalization using ND280 measurement:

$$N_{SK}^{\text{exp}} = R_{ND}^{\mu, Data} \times N_{SK}^{MC} / R_{ND}^{\mu, MC}$$

- Evaluate systematics
- Evaluate confidence intervals for data sample

Neutrino Flux and Modeling





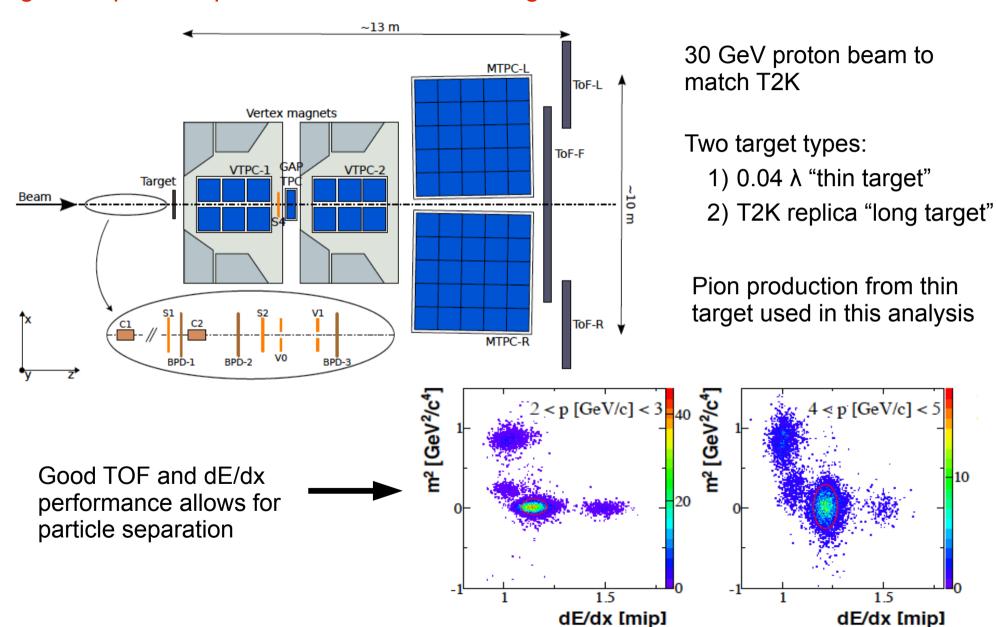
Flux Simulation:

- Proton beam monitor measurements as inputs
- In Target Hadron Production:
 - NA61 experimental (at CERN) data to model π[±] production
 - Kaon production, other hadron interactions model with FLUKA
- Out of target interactions, horn focusing, particle decays
 - GEANT3 simulation
 - Interaction cross sections are tuned to existing external data

NA61 Experiment



Large acceptance spectrometer and time-of-flight detectors



NA61 Results



27

Measure 30 GeV proton cross section on carbon:

$$\sigma_{\rm prod} = 229.3 \pm 9.2 \ mb$$

Measure differential π± production multiplicity

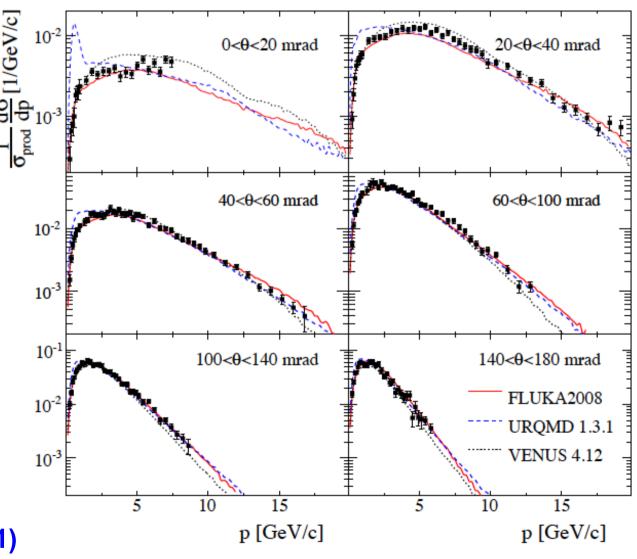
Systematic uncertainties of 5-10% for each point in p-θ space

2.3% normalization uncertainty

Uncertainties propagated into oscillation analysis

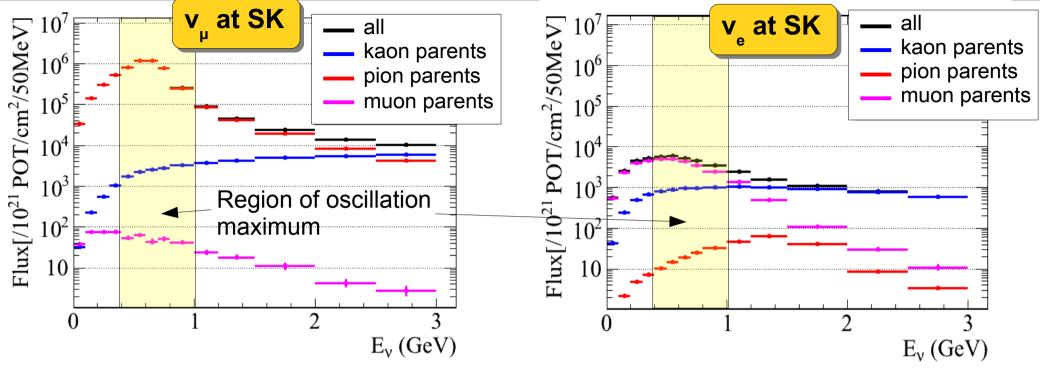
FLUKA does a good job of reproducing the NA61 data

N.Abgrall et al., arXiv:1102.0983 [hep-ex] accepted by Phys.Rev.C (2011)

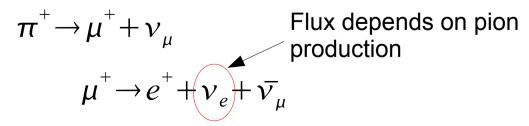


Neutrino Flux Prediction





- Muon neutrino flux around oscillation maximum predominantly from pion decays
- Intrinsic electron neutrino flux in beam from muon and kaon decays ~1% of total flux below 1 GeV
 - Dominant source around oscillation maximum is from muon decays



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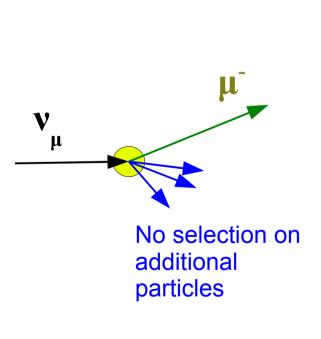
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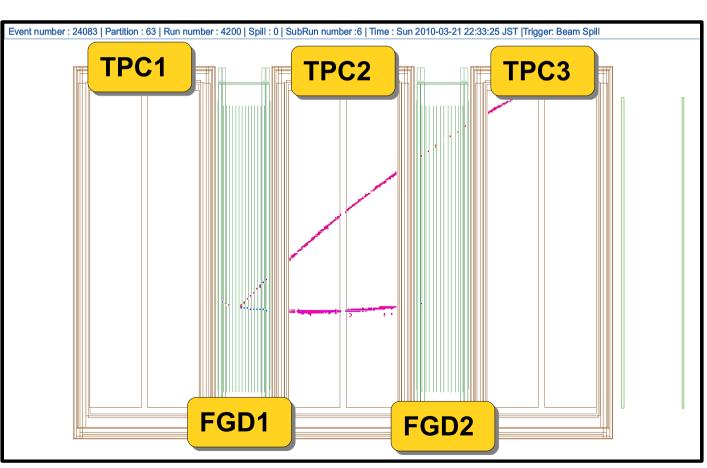
ND280 Inclusive v_{...} Analysis



- Analysis using low level reconstructed objects
 - Select negative μ-like tracks originating in FGDs and tracked by TPCs

 - For 2.88x10¹⁹ POT (Run 1): 1529 events

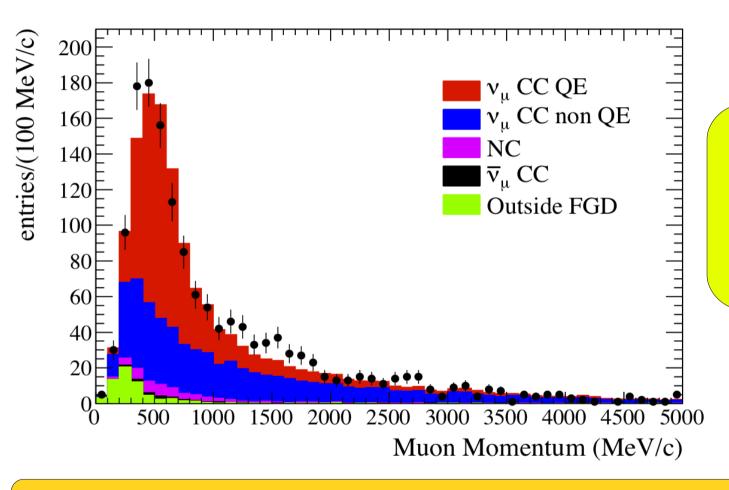




ND280 Inclusive v. Sample



Data and MC prediction for 2.88x10¹⁹ POT:



Comparison to POT normalized MC:

NA61+FLUKA flux model

NEUT neutrino interaction model

 $R_{ND}^{\mu,Data}/R_{ND}^{\mu,MC} = 1.036 \pm 0.028 (stat.)_{-0.037}^{+0.044} (det. sys.) \pm 0.038 (phys. model)$



Dominant sources: dE/dx and FGD/TPC matching

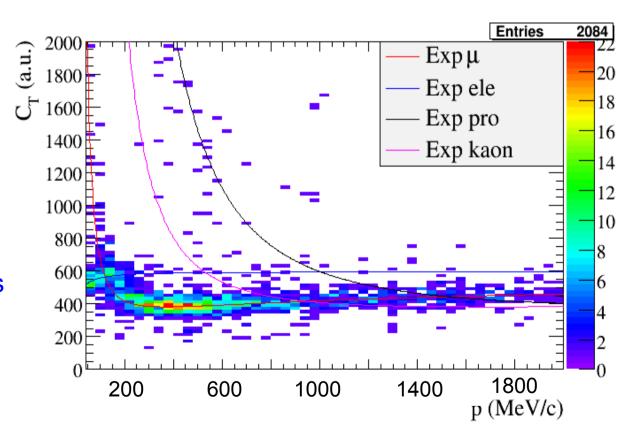
ND280 v Analysis



- ND280 $\nu_{_{e}}$ rate measurement using similar method as $\nu_{_{\mu}}$ measurement, same data set (Run1, 2.88x10 19 POT)
 - Use TPC dE/dx measurement to select electrons instead of muons
 - Reject events with second track that makes M_{inv} < 100 MeV/c² with electron candidate → reject photon conversions

Background sources:

- 1) Photons produced outside FGD that convert in the FGD (Out of FGD)
- 2) $\nu_{_{\mu}}$ interactions with γ from π^{0} that converts
- 3) v_{μ} interactions where muon is misidentified as an electron



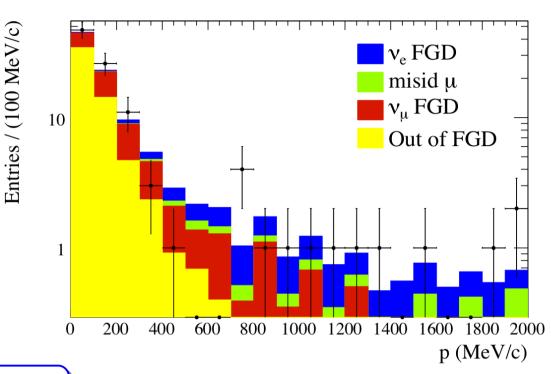
ND280 v Analysis Results



Fit data with signal and background templates \rightarrow extract $v_{\rm e}$ signal events

Data based template for misid μ

MC based templates for Out of FGD and v_{μ} FGD constrained by control samples



v_{e} Events from fit:

$$N_{sel}(v_e) = 7.8 \pm 5.5 (stat.) \pm 2.1 (syst.)$$

Dominated by uncertainty from fitting the photon conversion sample

$$\frac{N(\nu_e)}{N(\nu_\mu)} = \frac{N_{sel}(\nu_e)\epsilon(\nu_e)}{N_{sel}(\nu_\mu)\epsilon(\nu_\mu)} = (1.0 \pm 0.7(stat.) \pm 0.3(syst.))\%$$

$$\left[\frac{N(\nu_e)}{N(\nu_\mu)}\right]_{data} \div \left[\frac{N(\nu_e)}{N(\nu_\mu)}\right]_{MC} = 0.6 \pm 0.4 (stat.) \pm 0.2 (syst.)$$

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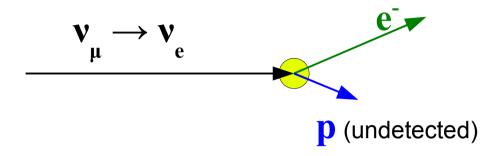


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ν Signal & Background at SK

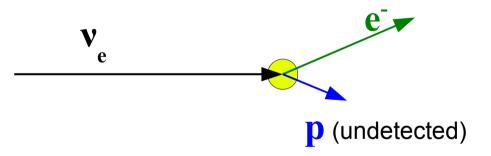


Oscillation Signal:

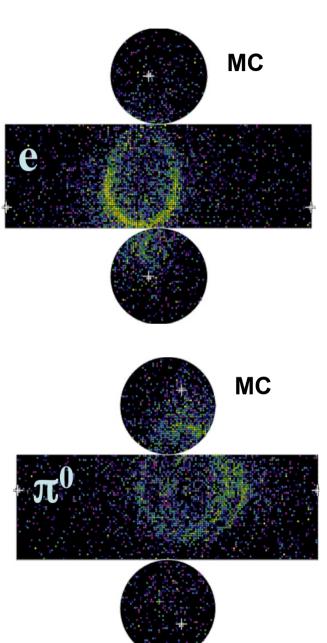


Identical for given neutrino energy.

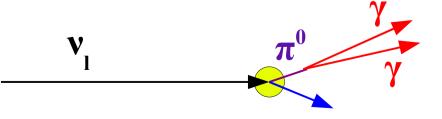
Beam v_e Background:



Beam background has harder spectrum



Neutral Current π⁰:



Can be removed by identifying second photon ring

N+others (undetected)

ν_e Selection at SK (7 Steps)



SK cross section view

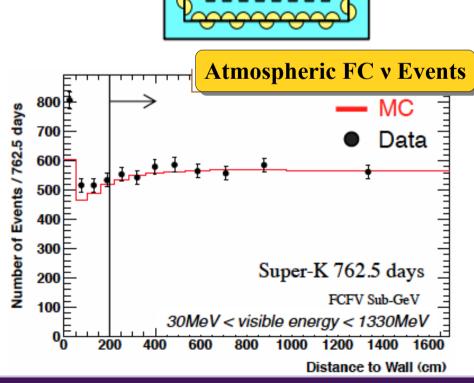
Select a single ring e-like sample, minimize beam and NCπ⁰ backgrounds

Optimized for current statistics

Cuts fixed before looking at data

1. Event falls in beam timing window, is fully contained in the inner detector (ID) (no activity in the OD)

- 2. Event vertex is >200 cm from the ID wall (fiducial volume cut)
 - If particle direction is towards
 nearest wall: ring size ~ PMT spacing
 - Rejects events originating in OD
 - 22.5 kton within fiducial volume

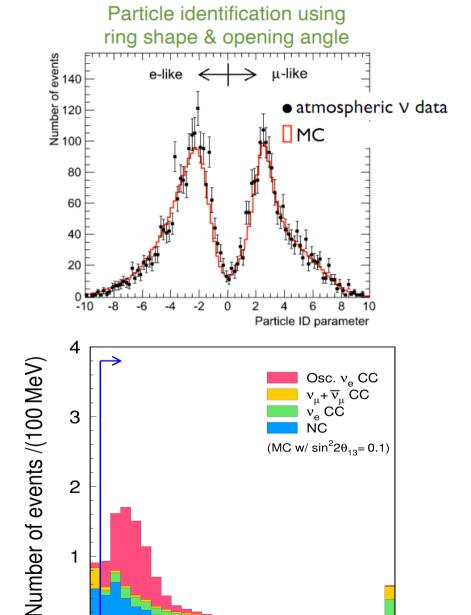


ν_a Selection at SK, Cont.



- 3. Select a single e-like ring
 - Particle ID based on ring shape
 - Good e/µ separation
 - Performance understood on atm. sample
 - ~1% probability to mis-ID μ as e

- 4. Visible energy > 100 MeV
- Low energy events = NC background and electrons from μ decay



1000

Visible energy (MeV)

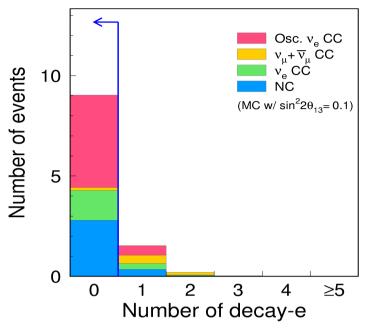
2000

3000

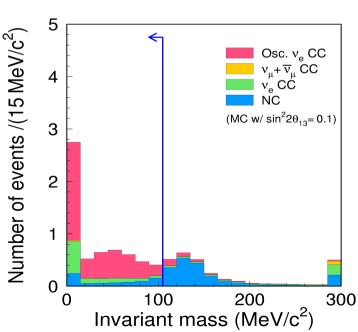
ν_e Selection at SK, Cont.



- 5. No decay electrons
 - Reject based on delayed activity in SK
- Rejects events with μ or π below threshold or misidentified as electron



- 6. π^0 mass cut, M_{inv} < 105 MeV/c²
 - Calculate invariant mass with 2-ring hypothesis for each event
 - Rejects NCπ⁰ background

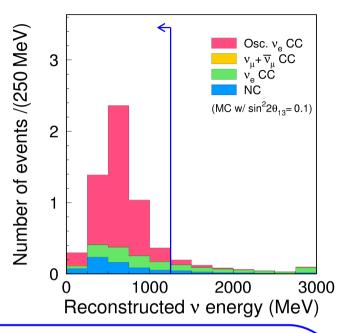


ν_e Selection at SK, Cont.



- 7. Reconstructed neutrino energy < 1250 MeV
 - Reject higher energy intrinsic beam background from kaon decays

Signal Efficiency = 66%
Background Rejection:
77% for beam v_e
99% for NC



Recall expected number of events is rescaled by Data/MC rate measured at ND280:

$$N_{SK}^{\exp} = R_{ND}^{\mu, Data} \times N_{SK}^{MC} / R_{ND}^{\mu, MC}$$

Sources	N exp SK
NC background	0.6
Beam $\nu_{_{_{e}}}$ background	8.0
Osc. through $\theta_{_{12}}$	0.1
$_{_{\mu}}$ CC background	0.03
Total	1.5±0.3

systematic error on following slides

Systematic Uncertainties



Where do systematic uncertainties enter?

$$N_{SK}^{\text{exp}} = R_{ND}^{\mu, Data} \times N_{SK}^{MC} / R_{ND}^{\mu, MC}$$

$$= \frac{\int \Phi_{\nu_{\mu}(\nu_{e})}^{SK}(E_{\nu}) \cdot P_{osc}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \epsilon_{SK}(E_{\nu}) dE_{\nu}}{\int \Phi_{\nu_{\mu}}^{ND}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \epsilon_{ND}(E_{\nu}) dE_{\nu}} \frac{M_{SK}}{M_{ND}} \cdot POT_{SK}$$

- ND280 statistical uncertainty
- Flux uncertainty → expect cancellation in ratio
- Neutrino interaction cross section uncertainties
- SK reconstruction, selection uncertainties
- ND280 reconstruction, selection uncertainties

Flux Uncertainty



Uncertainties on hadronic interactions dominate:

$$\frac{\int \boldsymbol{\Phi}_{\nu_{\mu}(\nu_{e})}^{SK}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{P}_{osc}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{\sigma}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{\epsilon}_{SK}(\boldsymbol{E}_{\nu}) \, d\boldsymbol{E}_{\nu}}{\int \boldsymbol{\Phi}_{\nu_{\mu}}^{ND}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{\sigma}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{\epsilon}_{ND}(\boldsymbol{E}_{\nu}) \, d\boldsymbol{E}_{\nu}}$$

- 1. Pion production: systematic uncertainties from NA61
- 2. Kaon production: from comparison of FLUKA to external data
- 3. Secondary nucleon production: comparison of FLUKA to external data
- 4. Hadron interaction probabilities: from external measurements of π , p, K cross sections

Percent Errors from Flux Uncertainties (θ_{13} =0)

Error Sources	$R_{\text{ND}}^{~\mu,\text{MC}}$	$N_{\rm sk}^{\rm MC}$	$N_{sk}^{MC}/R_{ND}^{\mu,MC}$	
Pion Production	5.7%	6.2%	2.5%	
Kaon Production	10.0%	11.1%	7.6%	Cancellation works best
Other Hadron Int.	9.7%	9.5%	1.5%	for neutrinos from pion production
Beam Direction, Alignment, Horn Current	3.6%	2.2%	2.3%	
Total	15.4%	16.1%	8.5%	

v Cross Section Uncertainties

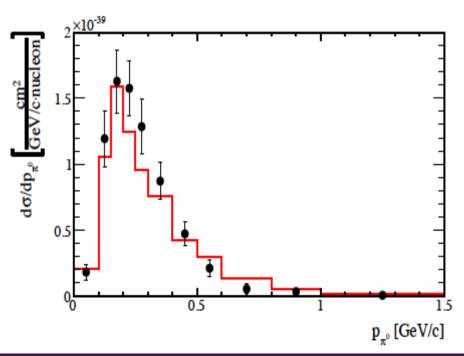


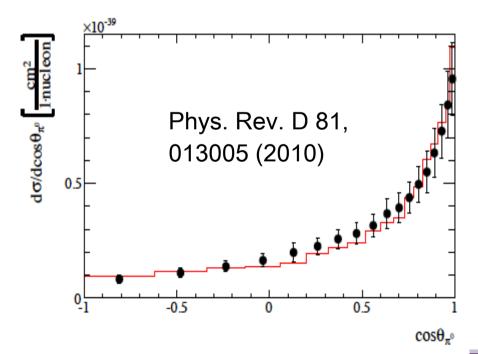
Nominal cross sections from NEUT model Cross section uncertainties from:

$$\frac{\int \boldsymbol{\Phi}_{\nu_{\mu}(\nu_{e})}^{SK}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{P}_{osc}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{\sigma}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{\epsilon}_{SK}(\boldsymbol{E}_{\nu}) d\boldsymbol{E}_{\nu}}{\int \boldsymbol{\Phi}_{\nu_{\mu}}^{ND}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{\sigma}(\boldsymbol{E}_{\nu}) \cdot \boldsymbol{\epsilon}_{ND}(\boldsymbol{E}_{\nu}) d\boldsymbol{E}_{\nu}}$$

- 1. Comparisons of models to data: MiniBooNE, SciBooNE, SK atmospheric
- 2. Variation of model parameters: M_A, binding energies...
- 3. Comparisons between models: relativistic fermi gas vs. spectral function

NEUT comparison to MiniBooNE NCπ⁰ diff. cross section





v Cross Section Unc. Summary



$\int \Phi_{\nu_{\mu}(\nu_{e})}^{SK}(E_{\nu}) \cdot P_{osc}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \epsilon_{SK}(E_{\nu}) dE_{\nu}$
$\int \Phi_{\nu_{\mu}}^{ND}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \epsilon_{ND}(E_{\nu}) dE_{\nu}$

		$\int {m \Phi}_{{\scriptscriptstyle {m u}}_{\mu}}^{\scriptscriptstyle {ND}}(E_{\scriptscriptstyle {m u}}) \cdot {m \sigma}(E_{\scriptscriptstyle {m u}}) \cdot {m \epsilon}_{\scriptscriptstyle {ND}}(E_{\scriptscriptstyle {m u}}) dE_{\scriptscriptstyle {m u}}$
Error Sources	$N_{\sf SK}^{\sf exp}$	Relativistic fermi gas model vs
CCQE low energy	3.1%	— effective spectral function
CC 1π	2.2%	From studies of MiniBooNE
CC Coherent π	3.1%	data
CC Other	4.4%	From studies of SciBooNE data
NC $1\pi^0$	5.3%	
NC Coherent π	2.3%	
NC Other	2.3%	
$\sigma(v_{_{ m e}})$	3.4%	Dominant source is uncertainty on
FSI	10.1%	— pion final state interactions
Total	14.0%	Studied by adjusting NEUT microscopic pion cross section model and comparing to pion cross

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section data

SK Detector Systematic Unc.



Data driven evaluation of systematic uncertainties

$\int \Phi_{\nu_{\mu}(\nu_{e})}^{SK}(E_{\nu}) \cdot P_{osc}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot$	$\epsilon_{\it SK}(E_{\it v})$	dE_{ν}
$\int oldsymbol{\Phi}_{\scriptscriptstyle {V}_{\mu}}^{\scriptscriptstyle ND}(E_{\scriptscriptstyle {\scriptscriptstyle {\cal V}}}){\cdot}oldsymbol{\sigma}(E_{\scriptscriptstyle {\scriptscriptstyle {\cal V}}}){\cdot}oldsymbol{\epsilon}_{\scriptscriptstyle {ND}}(E_{\scriptscriptstyle {\scriptscriptstyle {\cal V}}})$	$(E_{\nu}) dE_{\nu}$	

Error source	$\frac{\delta N_{SK \nu_e sig.}^{MC}}{N_{SK \nu_e sig.}^{MC}}$	$\frac{\delta N_{SK\ bkg.\ tot.}^{MC}}{N_{SK\ bkg.\ tot.}^{MC}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron finding	0.1%	0.3%
Muon PID	-	1.0%
Total	7.6%	15%

Control sampledescribed on next slide

Evaluated on SK atmospheric sample

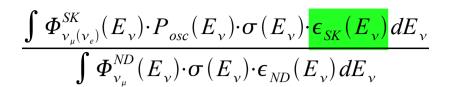
Uncertainty on signal

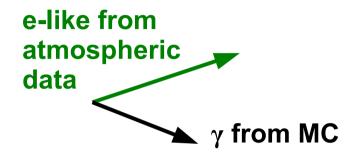
Uncertainty on background

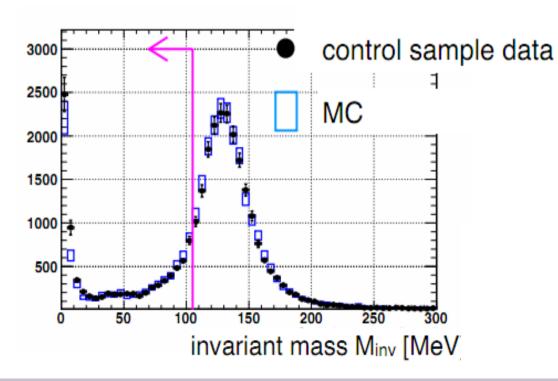
SK π⁰ Control Sample



- Special control sample needed to evaluate uncertainty from π^0 mass cut
- Select e-like rings from the atmospheric data set
- Add simulated γ to the event







- Two samples produced
 - More energetic ring from data
 - Less energetic ring from data
- Compare hybrid data+MC sample to pure MC sample
- Difference in efficiency used to calculate systematic uncertainty

Systematic Uncertainty Summary



Error Source	$\sin^2(2\theta_{13})=0$	sin²(2θ ₁₃)=0.1
Beam flux	8.5%	8.5%
v cross sections	14.0%	10.5%
ND280 detector	+5.6 % -5.2 %	+5.6 % -5.2
SK detector	14.7%	9.4%
ND280 statistics	2.7%	2.7%
Total	+22.8 -22.7 %	+17.6 % -17.5 %
		†

Smaller cross section and SK uncertainties for signal events

Outline



- Review of neutrino oscillations
- Overview of the T2K experiment
- Data collected by T2K
- Analysis chain
 - Flux prediction
 - Near detector measurement
 - Far detector selection
 - Systematic uncertainties

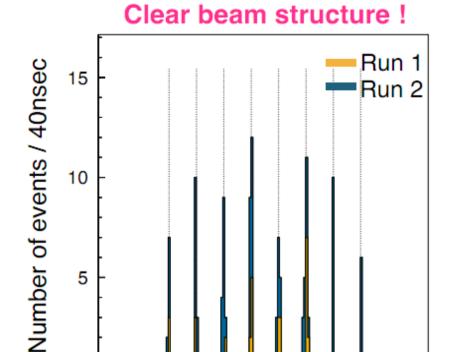


- Far detector data and interpretation
- Acknowledgements & Conclusions

SK Data Sample



- SK synchronized to beam timing using GPS
- SK events fully contained in the ID show clear beam time structure
- In total, 121 FC events
 - Non beam background from timing sidebands



-1000

1000 2000 3000 4000 5000

 ΔT_0 (nsec)

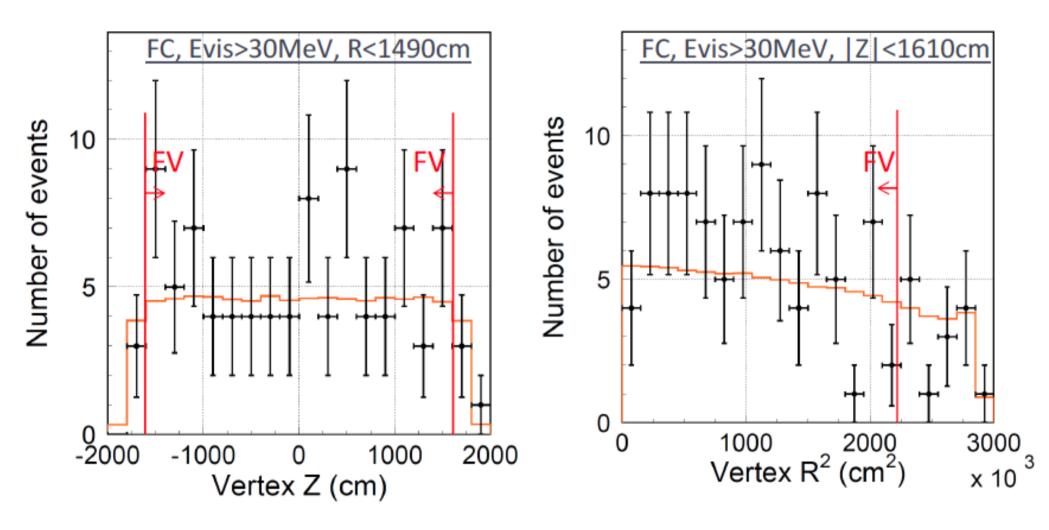
Number of events in on-timing windows (-2 \sim +10 μ sec)

	Class / Beam run	RUN-1	RUN-2		non-beam
	POT (x 10 ¹⁹)	3.23	11.08	14.31	background
Step	1: Fully-Contained (FC)	33	88	121	0.023

SK v Candidate Sample Selection



Step 2: Fiducial volume cut: vertex >200 cm from ID wall



121 → 88 Events

SK v Candidate Sample Selection

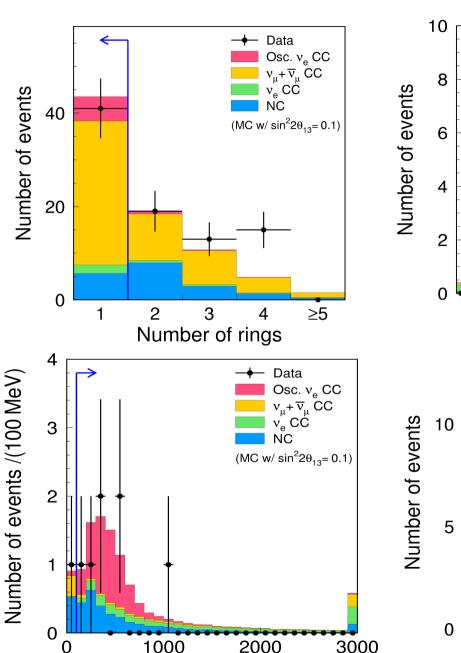


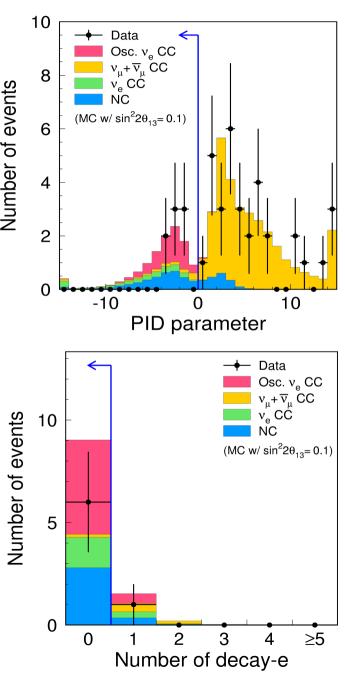
Step 3: Single e-like ring cut

88 → 8 Events

Step 4: Visible energy cut 8 → 7 Events

Step 5: Decay electron cut 7 → 6 Events





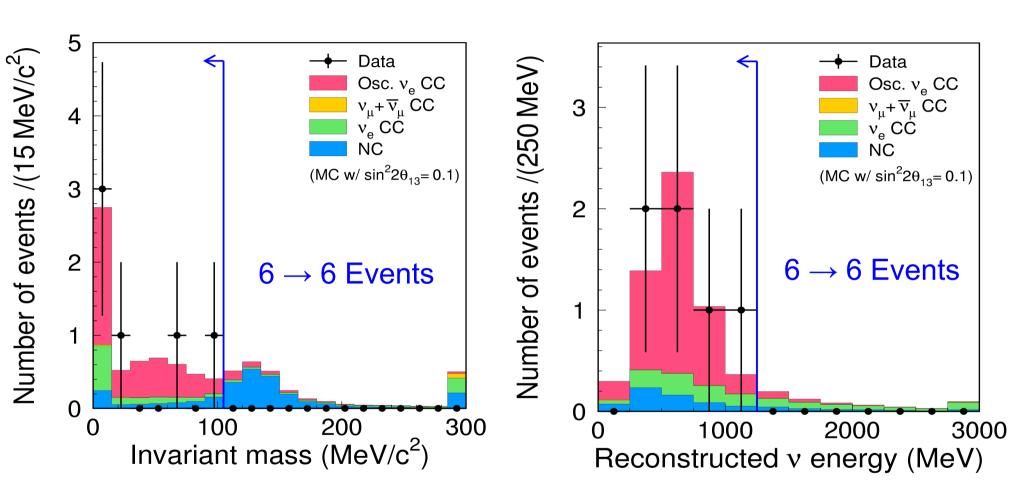
Visible energy (MeV)

SK v Candidate Sample



Step 6: π⁰ Mass Cut

Step 7: Reconstructed Energy Cut



After v_e selection is applied → 6 candidate events remain!

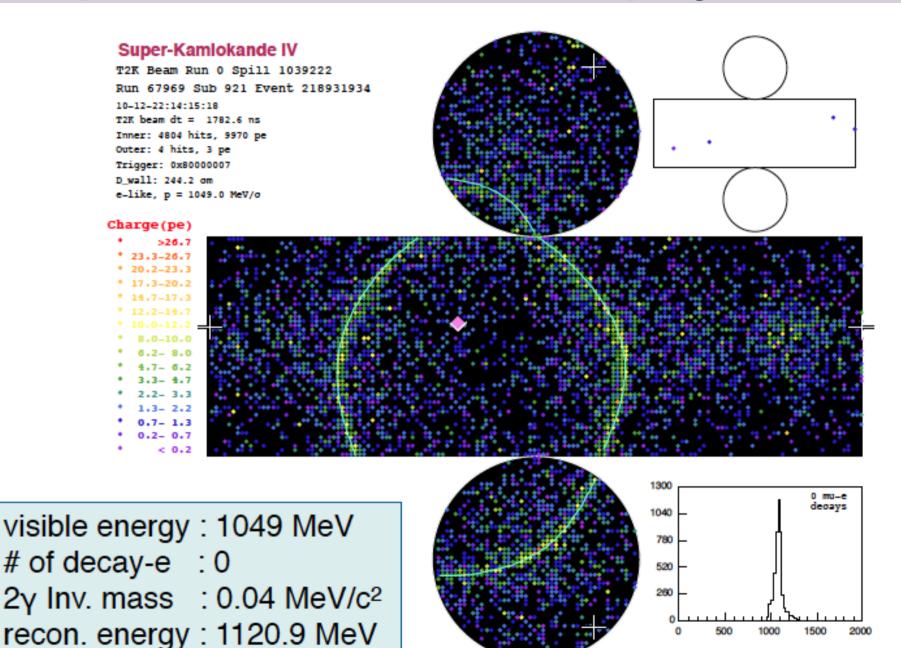
Recall, background expectation is 1.5 ± 0.3 events

Example Candidate Event Display



1500

Times (ns)



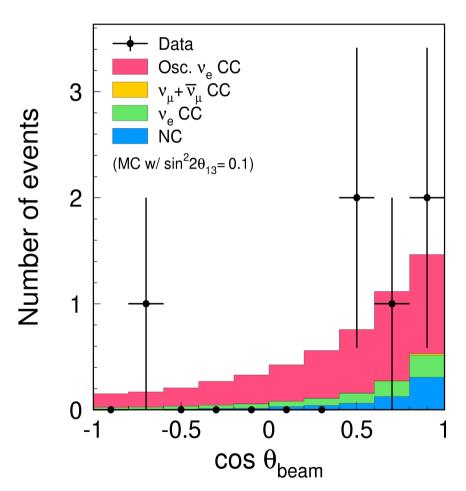
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Candidate Sample Checks



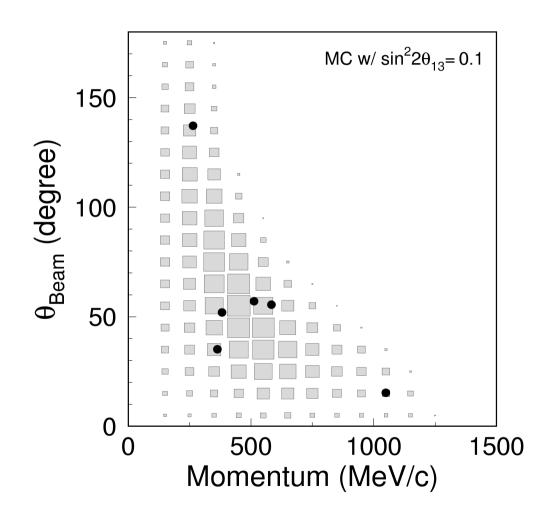
53

Reconstructed $cos(\theta_{beam})$:



 θ_{beam} = Lepton angle relative to beam direction

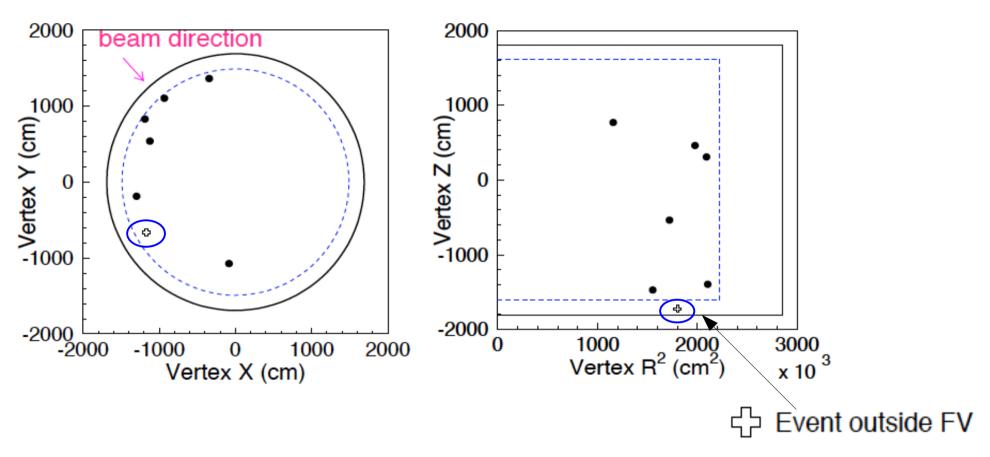
Reconstructed θ_{beam} vs. lepton momentum:



Vertex Distribution



Vertex distribution of candidate events:

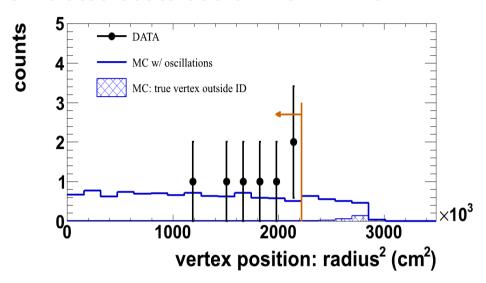


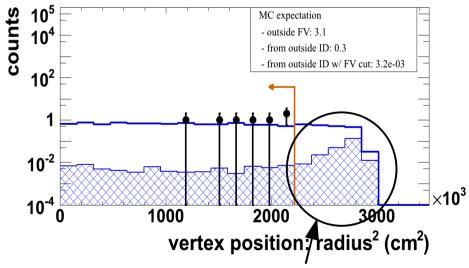
- KS test of R² distribution yields p-value = 0.03 (~1-20% for other distributions)
- Only one event seen outside fiducial volume that passes all other cuts
 - If beam related background from outside FV, expect more events in this region
- OD event distributions show no indication of contamination from outside ID

More on Vertex Distributions



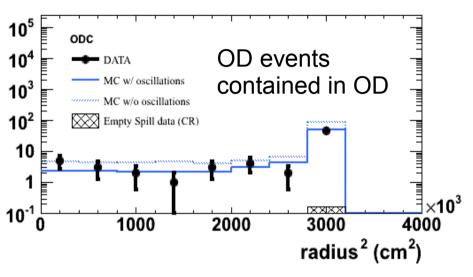
ID vertex distribution and MC with interactions simulated out to 550 cm from ID wall

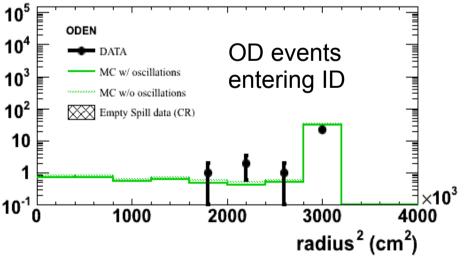




If outside source, expect more data at large R² outside FV

OD event vertex distributions:





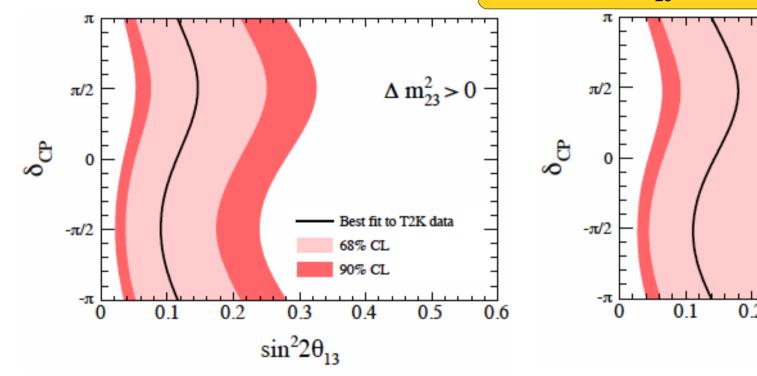
No significant data excess in OD samples

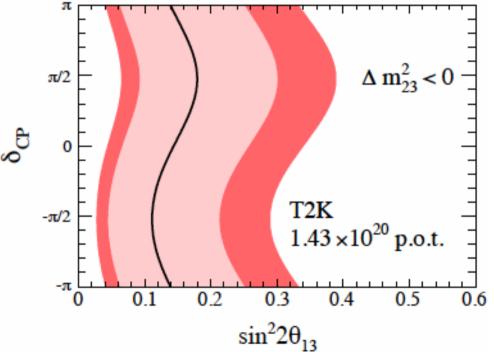
Interpretation for $\sin^2(2\theta_{13})$



For $\sin^2(2\theta_{13})=0$ [$\sin^2(2\theta_{23})=1.0$, $\Delta m_{23}^2=2.4\times10^{-3}$ eV²], probability to observe ≥ 6 events = 0.007

(fixing $\sin^2(2\theta_{23}) = 1.0$, $\Delta m^2_{23} = 2.4 \times 10^{-3} \text{ eV}^2$)





At $\sin^2(2\theta_{23})=1.0$, $\Delta m_{23}^2=2.4x10^{-3} \text{ eV}^2$, $\delta_{CP}=0$, 90% CL intervals are:

Normal hierarchy: $0.03 < \sin^2(2\theta_{13}) < 0.28$

Inverted hierarchy: $0.04 < \sin^2(2\theta_{13}) < 0.34$

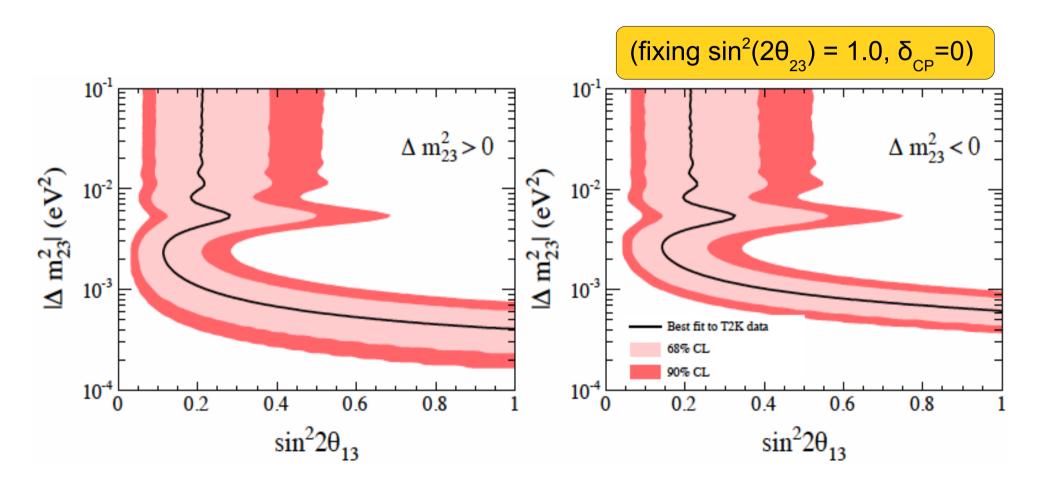
Best fit: $\sin^2(2\theta_{13}) = 0.11$

Best fit: $\sin^2(2\theta_{13}) = 0.14$

Contours in Δm^2

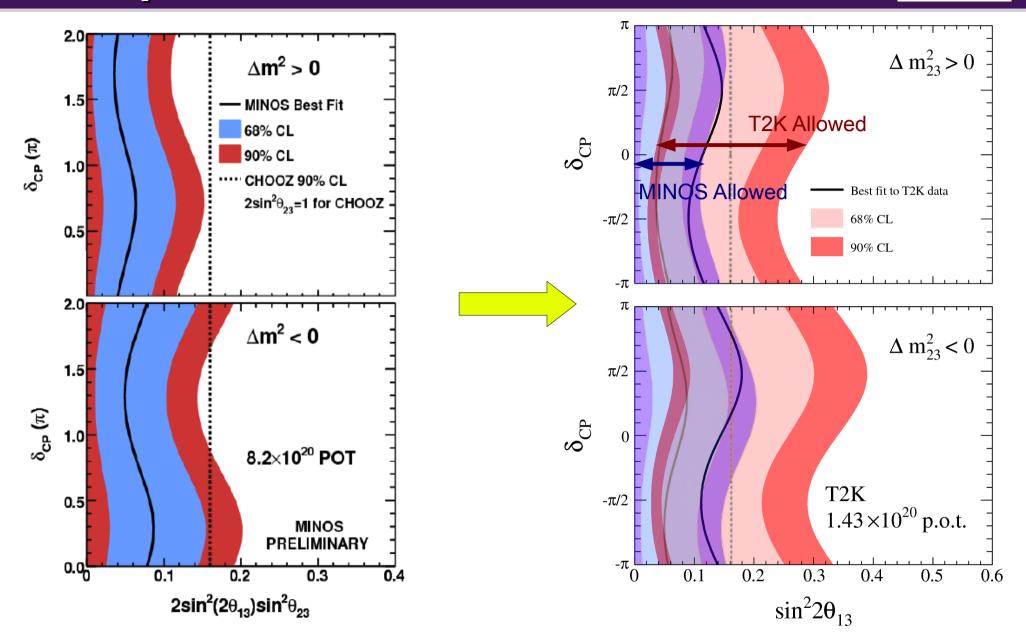


 $\sin^2(2\theta_{13})$ allowed region as function of $|\Delta m^2_{23}|$



Comparison to Recent MINOS Result JEK

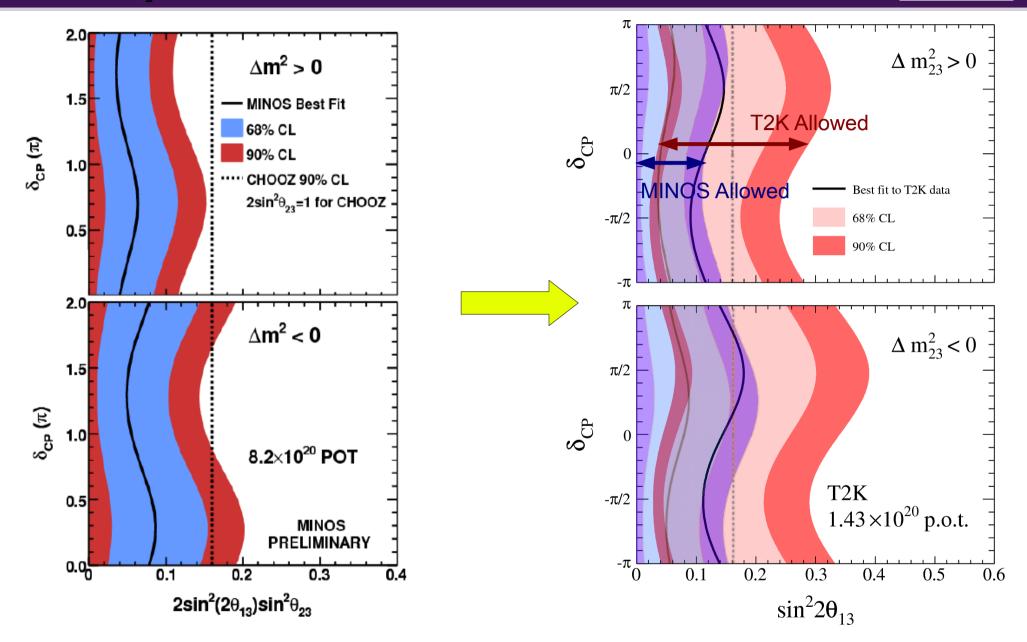




Significant overlap of T2K and MINOS 90% C.L. allowed regions

Comparison to MINOS Measurement





Significant overlap of T2K and MINOS 90% C.L. allowed regions

Next Steps for the v Analysis



Aim to firmly establish v_e appearance and better determine the θ_{13} mixing angle

- Resume experiment and collect more data
 - Recovery works in progress
 - No insurmountable problems found
 - Resumption of J-PARC activity including accelerator complex and neutrino facility by December, 2011
 - Neutrino facility ready by November
- Analysis improvements
 - New analysis methods using v_e shape information (e.g. recon. energy) are under development
 - ND280 measurements of v_{μ} CCQE spectrum, improvements to beam v_{e} , NC π^{0} measurements underway to better constrain flux and neutrino cross sections

Acknowledgements



- Significant hardware and intellectual contributions from Fermilab
 - Extruded scintillator for POD and Ecal
 - TRIP-t ASIC for POD, Ecal, SMRD, INGRID
 - Fiber mirroring for PDO, Ecal and FGD
 - Fiber extrusion technique developed at FNAL for FGD
 - MUMON beam test and ionization chamber design
 - Valuable input and support from the NBI community on the design of the beam line
 - Valuable input for the design of the OTR proton beam monitor
- T2K thanks Fermilab and all who contributed

Conclusion



- T2K reports new results on $v_{\mu} \rightarrow v_{e}$ oscillations based on 1.43 x 10^{20} p.o.t. (2% exposure of T2K's goal)
 - Expected number of events is 1.5 ± 0.3 ($\sin^2 2\theta_{13} = 0$)
 - 6 candidate events are observed
 - Under θ_{13} =0 hypothesis, the probability to observe 6 or more candidate events is 0.007 (equivalent to 2.5 σ significance)
 - 0.03 (0.04) $< \sin^2 2\theta_{13} < 0.28$ (0.34) at 90% C.L. for normal (inverted) hierarchy (assuming $\Delta m_{23}^2 = 2.4 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23} = 1$, $\delta_{CP} = 0$)
 - Accepted for publication by PRL. Preprint arXiv:1106.2822
- Work towards resumption of the experiment and improvement of analysis methods \to definitive measurements of the ${\rm v}_{\rm e}$ appearance phenomenon
- v_{μ} disappearance result with 1.43 x 10^{20} p.o.t. data will be reported at EPS this week



Backup Slides

Vertex Distribution Probabilities



- One must be careful when choosing distributions to test. If data guides choice, difficult to assign probability.
 - Choose distributions that we would check regardless of what is seen in data
- Can use KS test for the probability of the cumulative distribution
 - Concern about KS test for low statistics sample, so calculate probabilities from distributions of 100,000 toy MCs
- Probabilities for distributions of interest:

KS Toy MC Probabilities	6 FCFV Events	7 FC Events
Distance to nearest wall	3.7%	20.2%
From wall to beam	0.1%	1.3%
To wall to beam	1.2%	5.3%
R^2	3.1%	9.4%

For distributions relative to ID wall, it is more natural to include all 7 FC events

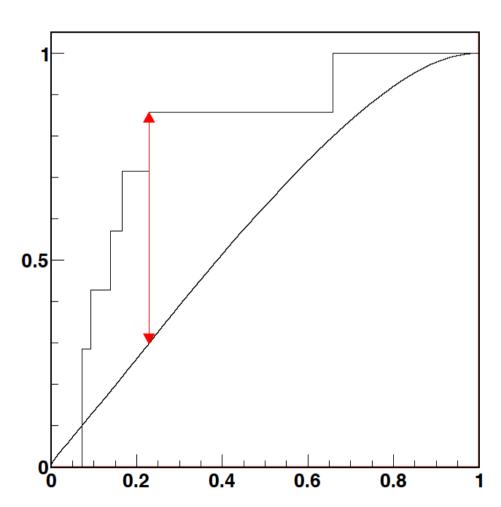
KS + Toy MC Example



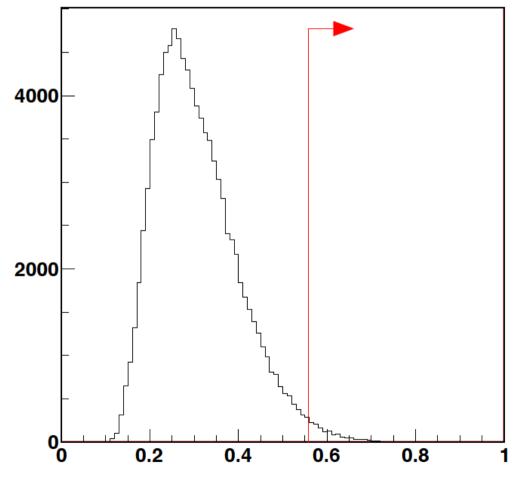
Cumulative distribution to extract maximum cumulative distance

p-value comes from toy MCs' distribution of maximum cumulative distance

Fromwall II to Beam of FC Events: Cummulative KS Distribution



Fromwall II to Beam of FC Events: Toy MC Distribution



MC Study of Sources Outside ID



Generated MC with events produced in material up to 550 cm outside of ID wall

Sources of beam-induced background with True Vertex outside the ID

Sample	Expected	Source of track, from MC truth*				
Sample	•	mis-id muon	pi0 photon	neutron	K-long	K-short
Nue Analysis Sample (w/ FV cut)	3.16E-03	9%	78%	11%	0.01%	<0.01%
Nue Analysis Sample (w/o FV cut)	0.30	4%	75%	3%	<0.01%	<0.01%

^{*}percentages do not total to 100% because list here is not exhaustive Expectation assumes $\sin^2 \theta_{13} = 0.1$, $\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$.

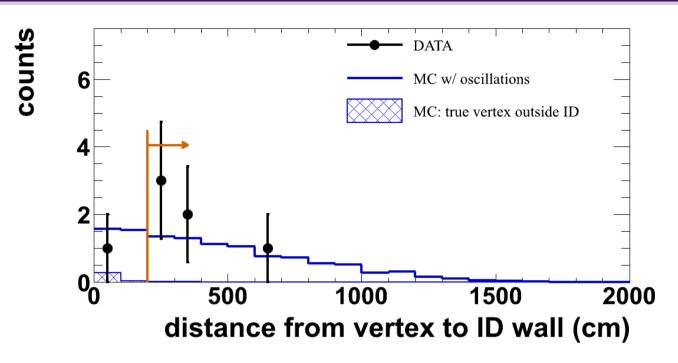
No significant contribution to FCFV sample simulated sources outside of ID

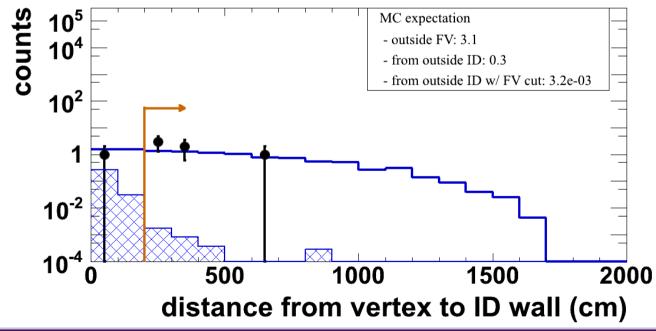
Distance to ID Wall



Expected and observed distance to ID wall

Prediction includes events with true vertex outside of ID





v_{...} Disappearance (Run 1)

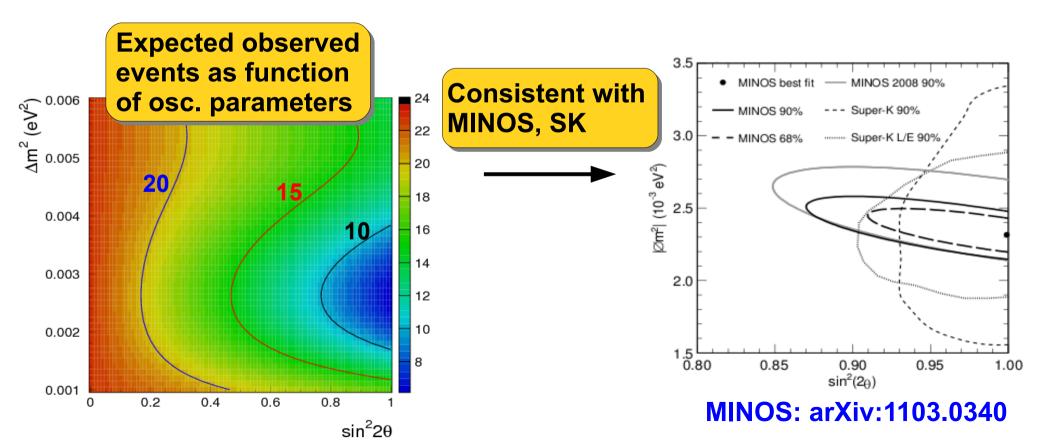


• 8 $\nu_{_{\mu}}$ candidate events observed at SK

• Expectation:

Osc. Hypothesis	Expected Events	Syst. Error
No oscillation	22.81	3.19
$\Delta m_{32}^{2} = 2.4 \times 10^{-3} \text{ eV}^{2}$	6.34	1.04
sin²(2θ ₂₃)=1.0		

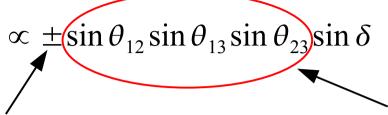
Update with Run 2 data and parameter fitting is underway



Measuring δ in v_{α} Appearance



Full appearance probability includes term that goes as $sin(\delta)$:



Sign flip for neutrino vs. antineutrino

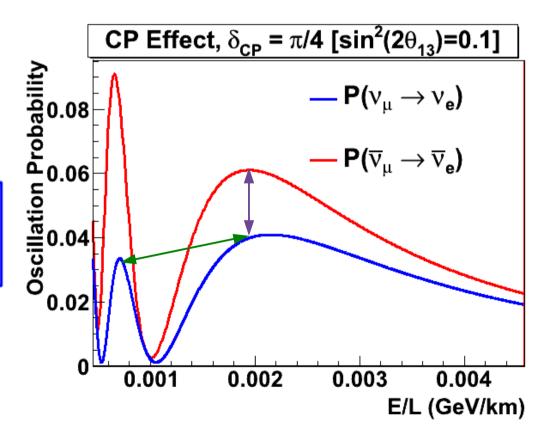
Need non-zero value for all three mixing angles including θ_{13}

Two ways to measure δ :

1. neutrino vs. antineutrino appearance probability

$$A_{CP} \equiv \frac{P - \overline{P}}{P + \overline{P}} \approx \frac{\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta$$

2. 1st vs 2nd oscillation maximum for neutrino mode



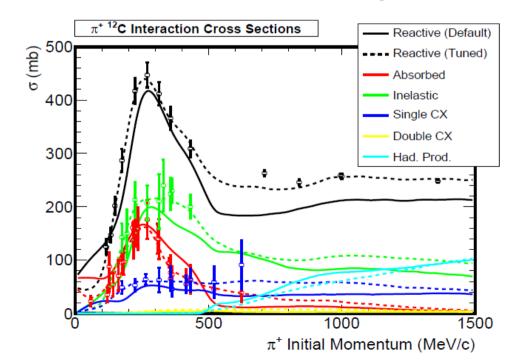
Final State Interactions



- Pions produced in the v interactions can interact in the target nucleus:
 - Absorption no pion in final state
 - Production additional pions in the final state
 - Charge exchange change of pion charge
- Microscopic (internal to nucleus) pion interaction model employed in NEUT
- Tune microscopic model to reproduce macroscopic pion scattering data

Tuning: vary microscopic mean free path for different interaction types and vary models

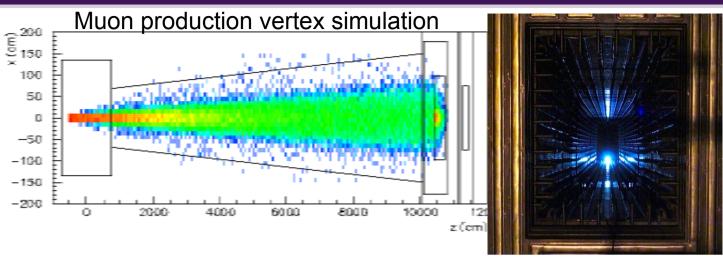
Tuned (dotted lines) in much better agreement with data



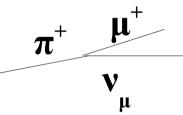
Decay Volume and MUMON



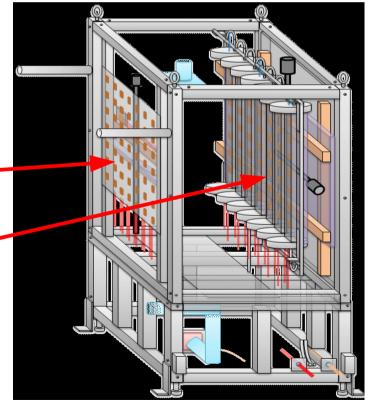
 Pions (and other particles) decay in 100 m long decay volume:



- MUMON muon monitor
 - Measures muons from pion decays

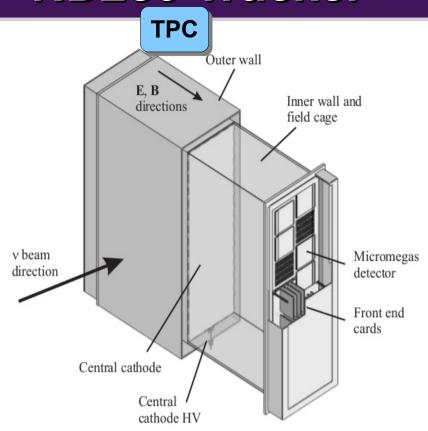


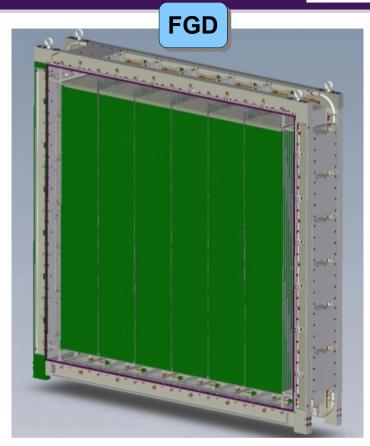
- Si PIN photodiodes sensitive at low intensity, but radiation damage
- Ionization chambers less suseptible to rad. damage
- Measure beam shape and direction



ND280 Tracker







- Track charged particles in magnetic field
- 10% momentum resolution at 1 GeV/c
- Neutrino target: 2.2 tonnes of material (including water targets)
- Tracking of particles

SK v Prediction Breakdown



75 %

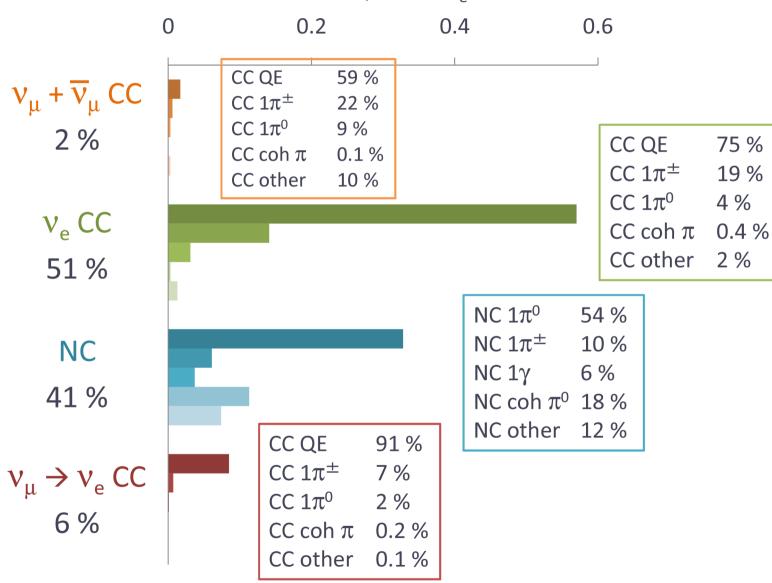
19 %

4 %

2 %

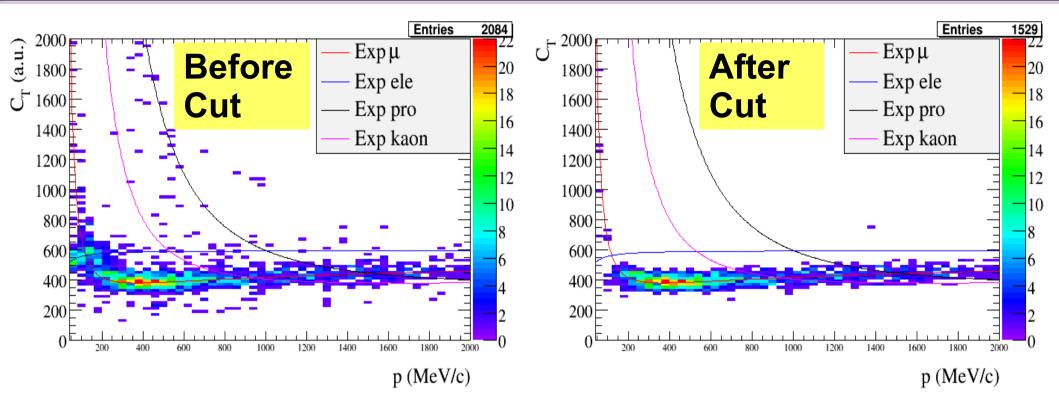


Number of expected v_e events



Particle ID with TPC dE/dx





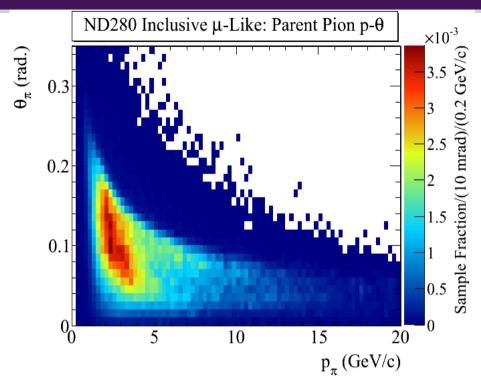
Two dE/dx Cuts:

$$|\delta_E(\mu)| < 2.5$$
, $|\delta_E(e)| > 2.0$ $\delta_E = dE/dx$ Pull

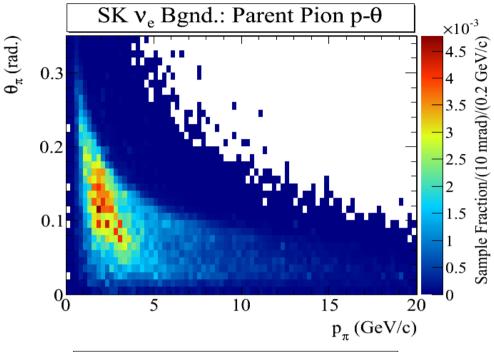
- Cut on TPC dE/dx with muon hypothesis to select muons
- Cut on TPC dE/dx with electron hypothesis to exclude electrons

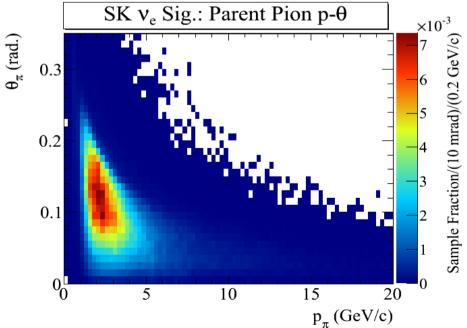
Parent Pion Phase Space





Plots show the p- θ distribution of parent pions contributing to the ND280 (upper left), SK nu_e background (upper right) and SK nu_e signal (lower left) samples. Plots are normalized to by the sample size, so the z axis is sample fraction. θ is the polar angle relative to the beam direction



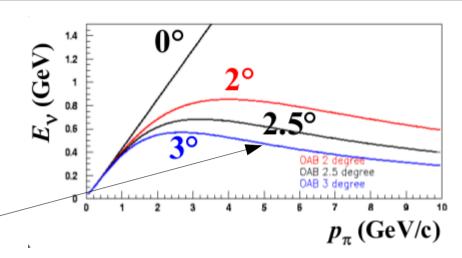


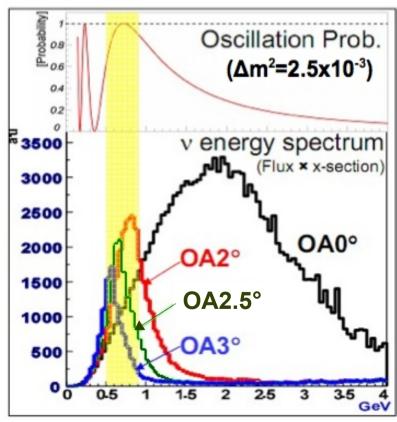
Why Off-axis?



- Pion decay kinematics:
 - In pion direction, neutrino energy proportional to pion momentum
 - At non-zero angles, weak dependence on pion momentum
- 2.5° off-axis angle gives narrow band beam peaked at the first oscillation maximum
 - More statistics in the oscillation region
 - Less feed-down from backgrounds at higher energy

Idea originally developed for long baseline proposal at BNL (E889)





SK Flux Plots



